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Measurement of Branching Fraction and *CP*-Violating Asymmetry for $B^0 \to \omega K^0_s$

The *BABAR* Collaboration

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Abstract

We present a preliminary measurement of the branching fraction and *CP*-violating parameters S and C for the decay $B^0 \to \omega K^0_S$. The data sample corresponds to 232×10^6 $B\overline{B}$ pairs produced from e^+e^- annihilation at the $\Upsilon(4S)$ resonance. We measure $\mathcal{B}(B^0 \to \omega K^0) = (5.9 \pm 1.0 \pm 0.4) \times 10^{-6}$, $S = 0.50^{+0.34}_{-0.38} \pm 0.02$ and $C = -0.56^{+0.29}_{-0.27} \pm 0.03$.

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1 Introduction

Evidence for the decay $B^0 \to \omega K^0$ was first seen by CLEO [1] with a significance of 3.9 standard deviations (σ). The decay was observed about a year ago with a sample of 89 million $B\overline{B}$ pairs by *BABAR* [2] with a significance of more than 7σ; the branching fraction was measured to be $\mathcal{B}(B^0 \to \omega K^0) = (5.9^{+1.6}_{-1.3} \pm 0.5) \times 10^{-6}$. More recently Belle has published evidence (significance 3.2σ) for this decay mode with a sample of 85 million $B\overline{B}$ pairs [3], finding a branching fraction of $(4.0^{+1.9}_{-1.6} \pm 0.5) \times 10^{-6}$. Belle also has a preliminary study with a sample of 275 million $B\overline{B}$ pairs of the time-dependence of the decay with a sample of about 30 events [4], though no branching fraction is reported.

The world average branching fraction, $(5.5^{+1.2}_{-1.1}) \times 10^{-6}$ [5], is somewhat larger than older theoretical predictions [6, 7, 8] and a more recent prediction using QCD factorization [9]. A very recent paper [10] finds an enhancement of the QCD factorization prediction by more than a factor of two due to final-state interactions, in excellent agreement with the world average. A phenomenological fit that uses SU(3) flavor symmetry and all available measurements of pseudoscalar-vector (PV) decays (branching fraction and *CP* asymmetry measurements for more than 30 charmless decay modes) finds a branching fraction of $(5.3^{+0.8}_{-0.4}) \times 10^{-6}$ for this decay [11].

In this paper we report improved branching fraction results for this decay as well as a measurement of the *CP* asymmetry parameters. In the Standard Model (SM), this decay is expected to proceed primarily through a penguin (loop) diagram as shown in Fig. 1a, though a Cabibbo- and color-suppressed tree diagram is also possible (Fig. 1b). Neglecting the suppressed amplitude, these decay modes have the same weak phase as the charmonium K^0 decays [12] which proceed through the Cabibbo-Kobayashi-Maskawa (CKM) favored $b \to c\bar{c}s$ amplitude. Thus the time-dependent asymmetry measurement for the decay $B^0 \to \omega K^0$ would yield the same value of $\sin2\beta$ as for the charmonium K^0 decays [14]. Tests of this equality have been made from similar B^0 decays which are expected to be dominated by penguin amplitudes such as those to the charmless final states ϕK^0, $\eta' K^0$, $K^+K^-K^0$, $\pi^0 K^0$ and $f_0(980)K^0$ [13].

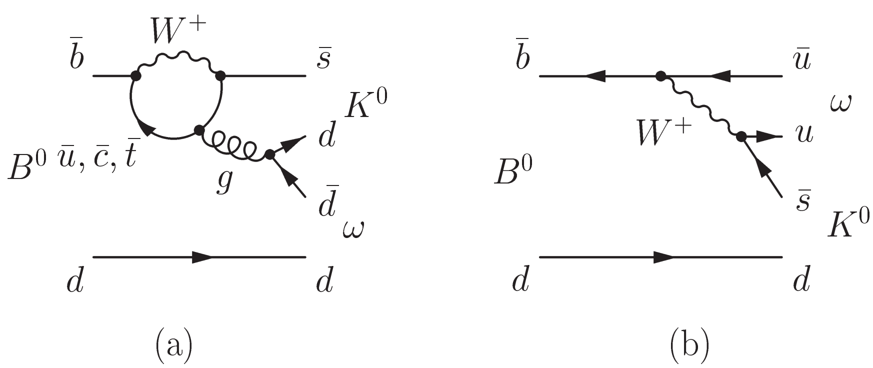

Figure 1: Feynman diagrams for the decay $B^0 \to \omega K^0$: (a) penguin diagram and (b) Cabibbo- and color-suppressed tree diagram.

Additional higher-order amplitudes and non-SM amplitudes carrying different weak phases would lead to differences between the measurements of the time-dependent *CP* violating parameter in these rare decay modes and in the charmonium K^0 decays. The recent calculation involving final-state interactions that was mentioned above [10] predicts an increase in $\sin2\beta$ of about 0.10 for

$B^0 \to \omega K^0$ due to the color-suppressed amplitudes, though this increase is nullified when final-state interactions are included.

2 The *BABAR* Detector and Dataset

The results presented here are based on data collected with the *BABAR* detector [16] at the PEP-II asymmetric e^+e^- collider located at the Stanford Linear Accelerator Center. We use a data sample with an integrated luminosity of 211 fb^{-1} recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). This corresponds to 232 million $B\overline{B}$ pairs. The asymmetric beam configuration in the laboratory frame provides a boost of $\beta\gamma = 0.56$ to the $\Upsilon(4S)$.

Charged particles from the e^+e^- interactions are detected and their momenta measured by a combination of a vertex tracker (SVT) consisting of five layers of double-sided silicon microstrip detectors and a 40-layer central drift chamber, both operating in the 1.5-T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter (EMC). Further charged particle identification (PID) is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring imaging Cherenkov detector (DIRC) covering the central region. The flux return of the solenoid is composed of multiple layers of iron and resistive plate chambers for the identification of muons and long-lived neutral hadrons.

3 Time-dependent Analysis

From a $B\overline{B}$ pair we reconstruct a B^0 or $\overline{B}^0$ decaying into the CP eigenstate $B^0 \to \omega K^0_S$ (B_{CP}). We also reconstruct the vertex of the other B meson ($B_{\rm tag}$) and identify its flavor. The time difference $\Delta t \equiv t_{CP} - t_{\rm tag}$, where t_{CP} and $t_{\rm tag}$ are the proper decay times of the signal and tagged B mesons, respectively, is obtained from the measured distance between the B_{CP} and $B_{\rm tag}$ decay vertices and from the boost ($\beta\gamma = 0.56$) of the $\Upsilon(4S)$ system. The distribution of Δt without detector resolution effects is:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left\{1 \mp \Delta w \pm (1-2w)\left[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right]\right\}, \tag{1}$$

where the upper (lower) sign denotes a decay accompanied by a B^0 ($\overline{B}^0$) tag, τ is the B^0 lifetime [17], Δm_d is the mixing frequency, and the mistag parameters w and Δw are respectively the average and difference of the probabilities that a true B^0 ($\overline{B}^0$) meson is tagged as $\overline{B}^0$ (B^0). The tagging algorithm [12] has seven mutually exclusive tagging categories of differing purities (including one for untagged events that we retain for the branching fraction determination). Separate neural networks are trained to identify primary leptons, kaons, soft pions from D^* decays, and high-momentum charged particles from B decays. Each event is assigned to one of these categories based on the estimated mistag probability and on the source of tagging information. The measured analyzing power, equal to the reconstruction efficiency times $(1-2w)^2$ summed over all categories, is $(30.5 \pm 0.6)\%$; this is determined from a large sample of B-decays to fully reconstructed flavor eigenstates ($B_{\rm flav}$). The parameter C measures direct CP violation. If $C = 0$, then $S = \sin 2\beta$ aside from the corrections discussed in the Introduction.

4 Event Selection and Analysis Method

To establish the event selection criteria, we use Monte Carlo (MC) simulations [18] of the signal decay modes, $B\overline{B}$ backgrounds, and detector response. We reconstruct B candidates by combining K^0_S and ω candidates. We select $K^0_S \to \pi^+\pi^-$ decays by requiring the $\pi^+\pi^-$ invariant mass to be within 12 MeV of the nominal K^0_S mass. We further require the three-dimensional flight distance from the beam spot to be greater than three times its uncertainty in a fit that requires consistency (fit probability greater than 0.001) between the flight and momentum directions. We reconstruct ω mesons through the primary $\omega \to \pi^+\pi^-\pi^0$ decay channel from two charged tracks and a π^0 candidate formed from pairs of photons with energy greater than 50 MeV and invariant mass between 120 and 150 MeV. The $\pi^+\pi^-\pi^0$ invariant mass is required to be between 735 and 825 MeV. For the time-dependent analysis, we require $|\Delta t| < 20$ ps and $\sigma_{\Delta t} < 2.5$ ps. We find an average of 1.13 B candidates per event. We choose the candidate with the $\pi^+\pi^-\pi^0$ mass nearest to the nominal ω mass [17].

For a correctly reconstructed B-meson candidate, the mass must equal the nominal B mass and the reconstructed energy must be equal to one-half the center of mass energy. Thus we characterize a candidate kinematically by the energy-substituted mass $m_{\rm ES} = [(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2]^{\frac{1}{2}}$ and energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. The resolution on ΔE ($m_{\rm ES}$) is about 30 MeV (3.0 MeV). We require $|\Delta E| \leq 0.2$ GeV and $5.25 \leq m_{\rm ES} \leq 5.29$ GeV, and include both of these observables in the maximum-likelihood (ML) fit (see Sec. 6).

5 Backgrounds

To reject background from continuum $e^+e^- \to q\overline{q}$ events ($q = u, d, s, c$), we use the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for combinations drawn from jet-like $q\overline{q}$ pairs and is nearly uniform for the isotropic B meson decays; we require $|\cos\theta_T| < 0.9$. The remaining continuum background dominates the samples.

We use MC simulations of $B^0\overline{B}^0$ and B^+B^- production and decay to investigate $B\overline{B}$ backgrounds. We estimate that this background comprises 0.2% of the fit sample. Since we estimate from simulation studies that this background would change the signal yield by less than one event, we do not include a $B\overline{B}$ component in the fit.

6 Maximum Likelihood Fit

We use two unbinned, multivariate maximum-likelihood fits, one to extract signal yields and and one to determine the *CP* violating parameters. The yield fit does not use the tagging and Δt information in order to reduce systematic errors from the Δt parameterization (though the yields are in excellent agreement for both fits). We use six discriminating variables: $m_{\rm ES}$, ΔE, Δt, the $\pi^+\pi^-\pi^0$ invariant mass (m_ω), a Fisher discriminant $\mathcal{F}$, and $\mathcal{H} \equiv |\cos\theta_H|$. The Fisher discriminant combines five variables: the polar angles, with respect to the beam axis in the $\Upsilon(4S)$ frame, of the B candidate momentum and of the B thrust axis; the tagging category; and the zeroth and second angular moments $L_{0,2}$ of the energy flow about the B thrust axis. The moments are defined by $L_k = \sum_i p_i \times |\cos\theta_i|^k$, where p_i is the momentum of track or neutral cluster i, θ_i is its angle in the $\Upsilon(4S)$ frame with respect to the B thrust axis and the sum excludes the B candidate daughters.

The helicity angle θ_H is the angle, in the ω rest frame, between the normal to the ω decay plane and the B direction. For each species j (signal or background) and each tagging category c, we define a total probability density function (PDF) for event i as

$$\mathcal{P}_{j,c}^{i} \equiv \mathcal{P}_j({m_{\rm ES}}^i)\mathcal{P}_j(\Delta E^i)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(m_\omega^i)\mathcal{P}_j(\mathcal{H}^i)\mathcal{P}_j(\Delta t^i, \sigma_{\Delta t}^i, c)\,, \tag{2}$$

where $\sigma_{\Delta t}^i$ is the error on Δt for the event i. With n_j defined to be the number of events of species j and $f_{j,c}$ the fraction of events of species j for each category c, we write the extended likelihood function for all events belonging to category c as

$$\mathcal{L}_c = \exp\Big(-\sum_j n_j f_{j,c}\Big)\prod_i^{N_c}(n_{\rm sig}f_{{\rm sig},c}\mathcal{P}_{{\rm sig},c}^i + n_{\rm bkg}f_{{\rm bkg},c}\mathcal{P}_{\rm bkg}^i), \tag{3}$$

where N_c is the total number of input events in category c. The total likelihood function for all categories is given as the product over the tagging categories. For the yield-only fits, we integrate over the tagging categories and the product is over the total number of events in the sample.

We maximize the likelihood function by varying a set of free parameters: S; C; signal and background yields; background shape of $\mathcal{F}$, ΔE, $m_{\rm ES}$, and $\pi^+\pi^-\pi^0$ mass; the fractions of background events in each tagging category; and six parameters representing the background Δt shape. We determine the PDF parameters for signal from simulation except for Δt, where we use the $B_{\rm flav}$ data sample discussed in Sec. 3. For the continuum background we use $(m_{\rm ES}, \Delta E)$ sideband data to obtain initial values, before applying the fit to data in the signal region. We parameterize each of the functions $\mathcal{P}_{\rm sig}(m_{\rm ES})$, $\mathcal{P}_{\rm sig}(\Delta E_k)$, $\mathcal{P}_j(\mathcal{F})$, $\mathcal{P}_{\rm sig}(m_\omega)$ and real ω component of $\mathcal{P}_{\rm bkg}(m_\omega)$ with either a Gaussian, the sum of two Gaussians or an asymmetric Gaussian function as required to describe the distribution. Slowly varying distributions (mass, energy or helicity-angle for continuum background and the combinatorial background component of $\mathcal{P}_{\rm bkg}(m_\omega)$) are represented by linear or quadratic dependencies. The peaking and combinatorial components of the background $\pi^+\pi^-\pi^0$ mass spectrum each have their own $\mathcal{H}$ shapes. The continuum background in $m_{\rm ES}$ is described by the function $x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right]$, with $x \equiv 2m_{\rm ES}/\sqrt{s}$ and ξ as a free parameter. The background Δt shape is the sum of a core Gaussian convolved with an exponential function and two "tail" Gaussian functions. To verify the simulated resolutions in ΔE and $m_{\rm ES}$, we use large control samples of the decays $B^- \to \pi^- D^0$ with $D^0 \to K^-\pi^+\pi^0$, which have a topology similar to that of the signal. Where the control data samples reveal differences from MC in $m_{\rm ES}$ or ΔE, we shift or scale the resolution function used in the likelihood fits.

Before applying the fitting procedure to the data to extract the signal yields we subject it to several tests. Internal consistency is checked with fits to ensembles of "experiments" generated by MC from the PDFs. From these we establish the number of parameters associated with the PDF shapes that can be left free in addition to the yields. Ensemble distributions of the fitted parameters verify that the generated values are reproduced with the expected resolution. The ensemble distribution of $\ln\mathcal{L}$ itself provides a reference to check the goodness of fit of the final measurement once it has been performed.

We evaluate biases from our neglect of correlations among discriminating variables in the PDFs by fitting ensembles of simulated experiments. Each simulated experiment has the same number of events as the data for both background and signal; background events are generated from the background PDFs while signal events are taken from the fully simulated MC samples. We find a positive bias of 7.3 ± 0.5 events. Since events from a weighted mixture of simulated $B\overline{B}$ background decays are included, the bias we measure includes the effect of the neglect of $B\overline{B}$ background in the fit.

7 Results

The results of the fits are shown in Table 1. The branching fraction is determined from the fit yield, corrected for the bias discussed above. The statistical error on the signal yield is equal to the change in value that corresponds to an increase of $-2\ln\mathcal{L}$ by one unit from its minimum. The significance is equal to the square root of the difference between the value of $-2\ln\mathcal{L}$ (with systematic uncertainties included) for zero signal and the value at its minimum. Results from simulated experiments suggest a possible underestimate of the fit error on S and C. To account for this effect, the statistical uncertainty for S and C have been increased by a factor of 1.07.

Table 1: Results from yield and Δt fits.

Quantity	Yield fit	Δt fit
Events in ML fit	9145	8070
Fit signal yield	96 ± 14	92 ± 13
Efficiency (ϵ)	0.21	–
$\prod \mathcal{B}_i$	0.31	–
$\epsilon \times \prod \mathcal{B}_i$	0.065	–
Significance	8.6	–
$\mathcal{B}(10^{-6})$	$5.9 \pm 1.0 \pm 0.4$	–
S	–	$0.50^{+0.34}_{-0.38}$
C	–	$-0.56^{+0.29}_{-0.27}$

In Fig. 2 we show projections onto $m_{\rm ES}$ and ΔE of a subset of the data for which the signal likelihood (computed without the plotted variable) exceeds a threshold that optimizes the sensitivity. In Fig. 3, we show plots of the Δt distribution for B^0- and $\overline{B}^0$-tagged events and their difference.

8 Systematic Uncertainties and Crosschecks

8.1 Branching Fraction Fit

Most of the systematic uncertainties arising from lack of knowledge of the PDFs have been included in the statistical errors since most background parameters are free in the fits. For the signal the uncertainties in PDF parameters are estimated from the consistency of fits to MC and data in control modes. Varying the signal PDF parameters within these errors, we estimate the uncertainties in the signal PDFs to be 0.7 events. The uncertainty in the fit bias correction is conservatively taken to be half of the correction itself.

The above uncertainties are additive in nature. There are also multiplicative systematic errors that are comparable in size, primarily uncertainties in the efficiency. The latter, found from auxiliary studies, include an uncertainty in the absolute efficiencies for tracking (1.4%), π^0 reconstruction (3.0%), and K^0_S reconstruction (2.1%). Our estimate of the systematic error in B counting is 1.1%. Published data [17] provide the uncertainties in the ω product branching fractions (1%). The uncertainty in the efficiency of the $\cos\theta_{\rm T}$ requirement is 0.5%. The total systematic error on the branching fraction is 0.4×10^{-6}.

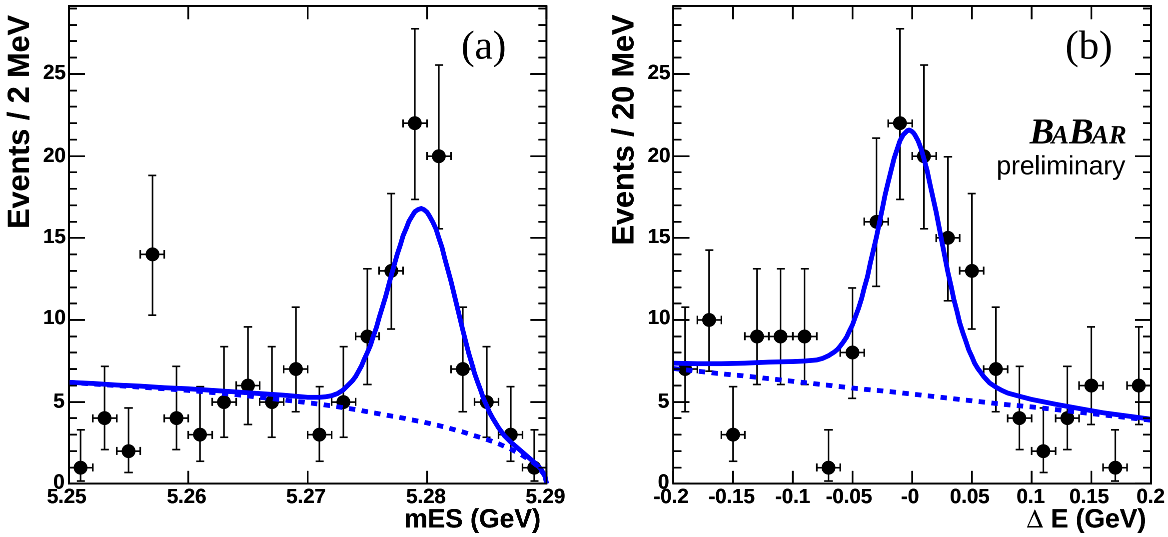

Figure 2: (a) $m_{\rm ES}$ and (b) ΔE projections for $B^0 \to \omega K^0_S$ for data subsets optimized from the signal likelihood. Points with error bars represent the data, solid curves the full fit functions, and dashed curves the background functions.

8.2 Δt Fit

The contributions to the systematic uncertainties in S and C are summarized in Table 2. We evaluate the uncertainties associated with the PDF shapes by variation of the parameters describing each discriminating variable that is not free in the fit. Systematic errors associated with signal parameters (Δt resolution function, tagging fractions, and dilutions) are determined by varying their values within errors. Uncertainties due to Δm_d and τ_B are obtained by varying these parameters by the uncertainty in their world average values [17]. All changes are combined in quadrature obtaining an error of 0.01 for both S and C.

We vary the SVT alignment parameters in the signal MC events by the size of misalignments found in the real data. The resulting uncertainty in both S and C is negligible.

For some tag-side B decays, there is interference between the CKM-suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude and the favored $b \to c\bar{u}d$ amplitude. We use simulation, allowing the full range of variation of the relevant parameters, to estimate the systematic errors due to this effect to be negligible for S and 0.015 for C. An uncertainty of 0.02 in S and C is assigned to account for limitations of Monte Carlo statistics and modeling of the signal. The uncertainty in the effect of the neglect of the small $B\overline{B}$ background is estimated to be less than 0.01 for both S and C. We find that the effects of the uncertainty in the position and size of the beam spot are negligible. The total systematic error is obtained by summing individual errors in quadrature.

When we fit with the value for C fixed to zero, we find a shift in S of 0.09, consistent with the correlation of $\sim$20% between these variables. We produce samples of pseudo-experiments generated with events produced to match the PDF distributions. From these samples, we verify that the fit bias on S and C is negligible and that there is a good agreement between expected and observed errors.

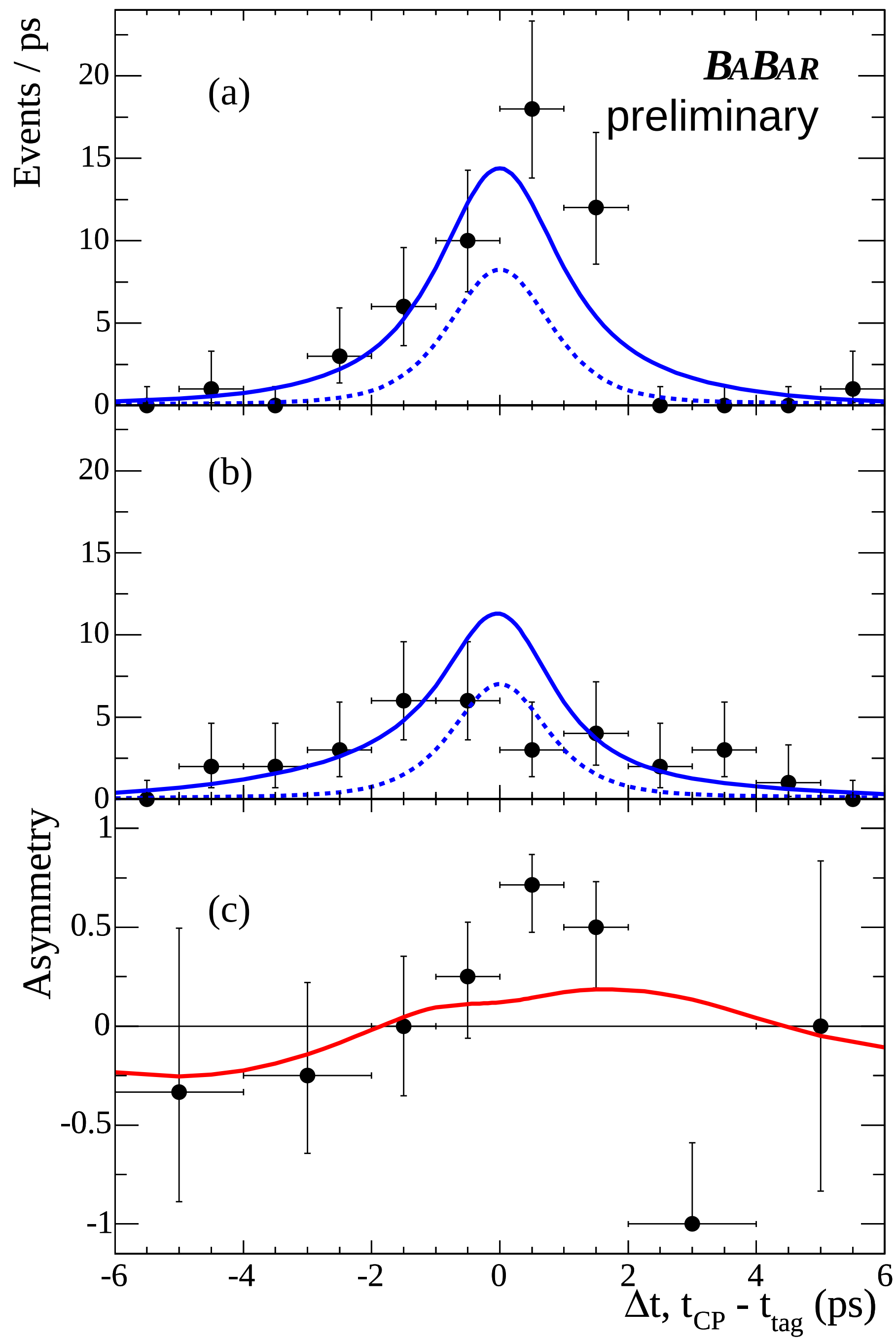

Figure 3: Projections onto Δt, showing the data (points with errors), fit function (solid line), and background function (dashed line), for (a) B^0 and (b) $\overline{B}^0$ tagged events and (c) the asymmetry between B^0 and $\overline{B}^0$ tags.

Table 2: Estimates of systematic errors.

Source of error	$\sigma(S)$	$\sigma(C)$
PDF Shapes	0.01	0.01
Tag-side interference	0.00	0.02
Δt modeling	0.02	0.02
$B\overline{B}$ background	0.01	0.01
Total	0.02	0.03

9 Conclusion

We use a reconstructed signal sample of 96 $B^0 \to \omega K^0_S$ events to determine the branching fraction, $\mathcal{B}(B^0 \to \omega K^0) = (5.9 \pm 1.0 \pm 0.4) \times 10^{-6}$. This value is in good agreement with previous measurements and with the world-average value for the charged mode $\mathcal{B}(B^+ \to \omega K^+) = 5.1 \pm 0.7$ [5]. This result is also in excellent agreement with the QCD factorization prediction modified by including final-state interactions [10] and with results from flavor-SU(3) fits to data for charmless B decays to PV final states [11].

We also measure the time-dependent CP-violating parameters to be $S = 0.50^{+0.34}_{-0.38} \pm 0.02$ and $C = -0.56^{+0.29}_{-0.27} \pm 0.03$. The measurement of C is consistent with zero and S is in good agreement with the value of $\sin 2\beta$ as measured in charmonium K^0 decays [12]. The value for S is also in agreement with, but more precise than, the Belle measurement $S = 0.75 \pm 0.64^{+0.13}_{-0.16}$ [4].

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